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Original article

Management of Stormwater through Green Infrastructure Systems in Coastal Urban Areas: Hydrological Modelling, Compound-Flood Response, and Water-Quality Performance

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Abstract
In seven different GI scenarios, a representative 120 ha coastal urban drainage catchment, typical of Alexandria, Egypt, on the Mediterranean coast of the Nile Delta, was analyzed using SWMM 5.2 with its low impact development (LID) extension. The scenarios included four single-practice scenarios: green roof, permeable pavement, bioretention cell, and infiltration trench, each aimed at mitigating 20% of the impervious area, and three mixed portfolios with targets of 10%, 20%, and 30% impervious areas (MIX10, MIX20, MIX30). The catchment has an area-weighted imperviousness of 81.9%, and drainage is discharged from the tide gate to receive storm surge, astronomical tide, and sea-level rise (SLR) scenarios of +0.0, +0.5, and +1.0 m, together with an incrementally diminishing infiltration capacity due to rising shallow coastal groundwater levels. For a 10-year 2-hour return period design storm of 39.7 mm, baseline simulation provided 0.79 runoff coefficient, 14.09 m^3/s of peak runoff, and 11,693 m^3 of system flooding. Scenarios MIX30 reduced 27.9%, 35.1%, and 59.5% of runoff volume, peak runoff, and flood volume, respectively. Permeable pavement resulted in the largest flood volume reduction (56.9%) among single practices. Efficacy of GI systems decreased with an increase in storm size, as flood-volume reduction for MIX30 varied from 88.6% for a 2-year storm to 42.9% for a 50-year storm. A SLR scenario of +1.0 m increased baseline flooding by 17.1% and MIX30 flooding by 30.5%, hence decreasing the flood-volume reduction efficacy of MIX30 from 59.5% to 54.8%, including 204 m^3 of water caused by limitations in infiltration associated with rising shallow groundwater level. Event loadings of total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) were reduced with MIX30 by 44.4%, 40.5%, and 39.6%, respectively. A Monte Carlo Analysis (60 runs for each scenario) revealed that differences between BL, MIX20, and MIX30 scenarios were statistically significant for all response variables (one-way ANOVA and Tukey's HSD, $p < 0.001$). From these findings, it follows that distributed GI can have a substantial effect on alleviating pluvial flooding in coastal low-lying areas; however, this effect is diminishing under both extreme rainfall events and rising sea levels and should be complemented by grey storm drainage systems and outfall management strategies within the overall coastal stormwater management program.
Keywords: Green Infrastructure; Low Impact Development; Storm Water Management; Coastal Cities; SWMM.

Introduction

Urbanisation replaces vegetated and permeable land with roofs, roads and paved surfaces. This alters the urban water cycle by increasing the volume and peak rate of surface runoff, shortening the time to peak and transporting sediments, nutrients and metals to receiving waters. Conventional ('grey') drainage manages these effects by conveying runoff as quickly as possible through pipes, but its capacity is fixed at the time of design and is increasingly exceeded by intense rainfall. Green infrastructure (GI)—also described as low impact development (LID), sustainable urban drainage systems (SUDS) or water-sensitive urban design (WSUD)—addresses runoff at its source through infiltration, retention, evapotranspiration and filtration, thereby restoring part of the pre-development hydrology [1].

Coastal cities face a particular form of this problem. Their drainage networks commonly discharge to the sea through low-gradient outfalls, so that high tides and storm surges reduce, or completely block, the outflow precisely when rainfall is heaviest. The joint occurrence of rainfall and elevated sea levels, termed compound flooding, has been shown to be increasing in frequency for major coastal cities [4], and sea-level rise (SLR) amplifies the flood hazard by raising the downstream boundary of both natural and engineered drainage systems [5]. Rising sea levels also lift the shallow coastal water table, which limits the vertical separation available for infiltration and can itself cause groundwater inundation of low-lying land [6].

Alexandria, the second-largest city of Egypt, exemplifies these pressures. The city lies on the north-western margin of the Nile Delta, a low-lying coastal plain that has been identified as highly vulnerable to SLR [3]. On 25 October and 4 November 2015, heavy rainfall from a frontal depression overwhelmed Alexandria's combined sewer and storm drainage system; approximately 60% of the city was flooded to depths of 0.5–1.0 m, some low-lying roads remained inundated for more than two weeks, and seven people died [2]. The event was attributed to a combination of extreme rainfall, ageing and undersized infrastructure, and rapid densification that reduced green and open space in the city [2]. The current situation reveals that Mediterranean coastal cities need more than just pipe capacity expansion to handle their growing hydraulic demand.

The current situation reveals that Mediterranean coastal cities need more than just pipe capacity expansion to handle their growing hydraulic demand. The way individual green infrastructure practices perform in terms of managing water is well known and has been studied a lot. Bioretention cells help reduce the amount of rainwater runoff and clean it by filtering out solid particles and dissolved pollutants [10]; permeable pavements collect and let rainwater soak into the ground below, while also catching dirt and debris [11]; and green roofs hold onto a large part of the rainfall that lands on them [12]. Studies

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at a large area level show that how well LID methods work depends a lot on how they are designed, the type of soil, the weather conditions, and the size of the storm [7, 8, 15]. Particularly, model studies show that the benefit of LID in reducing floods gets smaller when there is more rain and it comes down harder [9]. However, most of this evidence comes from inland temperate areas, where the water flows freely out and there are no limits on how much water can soak into the ground.

The EPA Storm Water Management Model (SWMM) and other process-based models offer a standardized approach to evaluating GI alternatives before investment. SWMM incorporates a non-linear reservoir runoff model with dynamic-wave routing of the drainage network and a dedicated LID module that mimics the layered storage, infiltration, and underdrain flow of individual practices. The model can also show how pollution is created using event mean concentration and how LID underdrain flow is treated [14], and it allows for changing outfall boundaries that follow tidal patterns over time. This mix of abilities makes it a good choice for looking at how coastal boundary conditions affect the benefits of green infrastructure.

This study aims to measure how well GI systems work for managing stormwater in low-lying coastal cities.To do this, it focuses on achieving the following goals: 1. Setting up a SWMM model for a coastal area that represents Alexandria's drainage system, which includes a tide-gated outfall that is affected by storm surges, tides, and sea level rise. Comparison of four single GI practices and three mixed GI portfolios that include more practices, all tested under design storms with return periods ranging from 2 to 50 years; 3. Evaluating how rising sea levels and higher groundwater levels together affect flooding and how green infrastructure helps; 4. Assessing the decrease in TSS, TN, and TP levels and checking how strong the results are when there is uncertainty in the parameters. Practical guidelines for the design of coastal GI in southern Mediterranean coastal cities are incorporated from the results.

Material and methodology:

Study Area and Catchment Characterisation

The study area is a coastal urban drainage area that covers 120 hectares.It is set up based on the land features, how the land is used, and the drainage system of the busy eastern parts of Alexandria, Egypt (31°12'N, 29°55'E).Water from this area flows north towards the Mediterranean Sea. The area was split into eight smaller parts called subcatchments (S1–S8), each between 11.4 and 18.5 hectares in size.These areas had a high percentage of impervious surfaces, ranging from 70% to 91%, with an average of 81.9% when calculated by area.This shows that the city has a lot of buildings, narrow streets, and not much green space [2]. The ground levels get lower from about 4.0 meters above average sea level at the start to 2.0 meters above average sea level close to the water's edge. The soils in the coastal area were sandy loams, which have a high ability to let water in at first, matching the calcareous sands found in the region. Runoff is gathered by a network of eight round concrete pipes (with diameters ranging from 0.9 to 1.8 meters and a total length of 2,880 meters) that all lead to one single drainage outlet (OF1), which is located at a depth of −0.10 meters above mean sea level.This outlet has a flap gate that controls the flow, especially during tidal changes. The network layout is shown in Figure 1, and the subcatchment characteristics are listed in Table 1.

Design Storms and Coastal Boundary Conditions

Design storms were created using 2-hour Chicago hyetographs, with rainfall data recorded every 5 minutes.The peak rainfall occurred at a ratio of 0.40 from the intensity-duration-frequency (IDF) relationship, which is given by the formula i = 430·T^0.25/(t + 10)^0.75.In this formula, i represents the rainfall intensity in millimeters per hour, T is the return period in years, and t is the duration in minutes. The IDF parameters were used to show the short, heavy rain events along the Alexandria coast.This means that the amount of rain expected in 50 years over 2 hours, which is 59.4 mm, matches the satellite data that found about 60 mm of rain each day during the October to November 2015 storms [2]. For return periods of 2, 5, 10, 25, and 50 years, the storm depths were 26.6, 33.4, 39.7, 49.9, and 59.4 mm respectively, and the highest 5-minute rainfall intensities ranged from 65.2 to 145.7 mm per hour (Figure 2a). The sea level at the outfall was set to η(t) = SLR + 0.40 + 0.15·cos[2π(t − 48 min)/12.42 h], which includes a storm surge of 0.40 meters, a semi-diurnal tide with an amplitude of 0.15 meters that represents the small tidal conditions along the Egyptian Mediterranean coast, and high water that happens at the same time as the highest rainfall, which is the most important situation for compound flooding [4]. The SLR scenarios of [3, 5] and [3, 5] (0.0, +0.5, +1.0 m) were analyzed (Figure 2b). Because SLR raises the coastal water table [6], the seepage rate from the LID storage layers dropped from 12 to 6 and 2 mm/h, and the minimum Horton infiltration rate fell from 12 to 7 and 3 mm/h, for the +0.0, +0.5, and +1.0 m scenarios, respectively. As shown in Table 1, each subcatchment flows into its own separate network node.

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Table 1. Characteristics of the Subcatchments of the Representative Coastal Catchment and Their Hydraulic Connection.

Sub-catchment	Area (ha)	Imperviousness (%)	Width (m)	Slope (%)	Outlet node (invert, m a.MSL)
S1	18.5	88	430	0.6	J1 (2.10)
S2	14.2	82	380	0.8	J2 (1.85)
S3	16.8	76	410	0.5	J3 (1.70)
S4	12.6	91	350	0.4	J4 (1.45)
S5	15.3	70	390	0.7	J5 (1.25)
S6	13.9	85	370	0.5	J6 (0.90)
S7	11.4	79	330	0.3	J7 (0.60)
S8	17.3	84	420	0.4	J8 (0.30)
Total / mean	120.0	81.9	—	—	OF1 (−0.10, tide gate)

SWMM Model Configuration and GI Scenarios

Stage I, which is the baseline model, calculated runoff using the non-linear reservoir method and Horton infiltration. The flow within the network was managed using the full dynamic-wave equations. The routing step was set to 5 seconds, while the wet-weather runoff was calculated every minute. The entire simulation ran for 12 hours. This setup allowed for the clear representation of surcharge, backwater from the outfall, and gate closure [13]. Water that went above the ground level at a node was marked as flooding and could not go back into the network (ALLOW_PONDING is set to NO). The SWMM LID module was used to simulate four single GI practices in Stage II, which included green roofs (GR) and permeable pavement (PP) as replacements for impervious surfaces and rain treatment, as well as bioretention cells (BC) and infiltration trenches (IT) for receiving runoff from nearby impervious surfaces with footprints of 6% and 4% of their contributing area. In each individual practice scenario (GR20, PP20, BC20, IT20), the practice handled 20% of the impervious area in every subcatchment. Stage III (Mixed portfolios): Three mixed scenarios (MIX10, MIX20, and MIX30) managed 10%, 20%, and 30% of the impervious area. Each scenario used a fixed mix of 25% green roofs (GR), 30% permeable pavements (PP), 30% bioretention cells (BC), and 15% infiltration trenches (IT). This mix was based on the typical availability of roofs, parking areas, sidewalks, and roadside verges in densely populated coastal areas. For each situation, the area and the amount of impermeable surface in each subcatchment were calculated after removing the areas covered by LID features. All scenarios were run for the five return periods with sea-level rise set at +0.0 meters. In addition, the baseline (BL), MIX20, and MIX30 scenarios were also run for the three sea-level rise scenarios, including both versions of MIX30 with and without the groundwater constraint.

Model Parameters

Subcatchments: Manning's n is 0.013 for impervious areas and 0.15 for pervious areas; depression storage is 1.5 mm and 5.0 mm; 25% of the impervious area does not have depression storage. With a decay constant of 4 h1 and a drying time of 7 d, Horton infiltration with f0 = 100 mm/h and f_c = 12 mm/h occurred. Conduits: Manning's n = 0.014. The GR has a surface area of 5 mm, a soil area of 80 mm with porosity, field capacity, wilting point, and a void fraction of 0.50. BC: berm 200 mm; soil 600 mm (with layers 0.45, 0.20, 0.10, and a saturated hydraulic conductivity of 100 mm/h); storage layer 300 mm (with a void ratio of 0.75); underdrain has a conductivity of 0.5, porosity of 0.5, and an offset of 150 mm. PP: pavement 100 mm (void ratio 0.15, permeability 250 mm/h); storage 300 mm (0.75); underdrain offset 50 mm. IT: storage 900 mm (0.75), no underdrain. Initial saturation of all LID layers 30%. Software: SWMM 5.2.4 engine (swmm-toolkit), Python 3, SciPy 1.18, statsmodels 0.15, Matplotlib 3.11.

Water-Quality Simulation and Statistical Analysis

Water quality: Following the event mean concentration (EMC) method used in SWMM [14], the total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) in surface runoff were measured at EMC levels of 135, 2.6, and 0.38 mg/L respectively. These values are common for areas with dense mixed urban land use. Treatment in the LID underdrain flow was shown to have consistent removal efficiencies of 85/45/60% (BC), 80/30/50% (PP), and 50/20/0% (GR) for TSS, TN, and TP, based on the ranges found in reviews of bioretention, permeable pavement, and green roof performance [10–12]; the retention and infiltration within these practices also helped reduce the load further. Event loads were calculated by measuring the amount of each pollutant that entered the drainage system. Uncertainty was studied using a Monte Carlo analysis for BL, MIX20, and MIX30 under the 10-year storm.For each situation, 60 different cases were created.In each case, the Horton infiltration rates, Manning's roughness, and LID seepage rate were randomly picked from ranges that were ±20% around their normal values. Imperviousness was also randomly chosen from a range of ±5%.A fixed random seed was used to make the results consistent. The results were shown as the average plus or minus the standard deviation. Tukey's HSD post hoc test was used in statistical analyses with one-way analysis of variance (ANOVA); a p-value of 0.05 was considered statistically significant. In every test, the volume continuity errors stayed under 0.03%.

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Results

Baseline Hydrological Response under Coastal Boundary Conditions

The model's schematic network and boundary conditions are illustrated in Figures 1 and 2. Under normal conditions, the area quickly produced runoff when it rained, with runoff coefficients between 0.78 and 0.83. These coefficients went up as the storm got deeper, because the areas that can soak up water were getting close to their limit in how much they could absorb (Table 2). The highest amount of water flowing over the surface went up from 8.31 cubic meters per second during a 2-year storm to 23.72 cubic meters per second during a 50-year storm. However, the amount of water leaving through the outfall stayed between 4.49 and 5.59 cubic meters per second.This shows that the system was limited by its capacity, and extra water either stayed in the pipes that were overflowing or caused flooding on the ground. Flooding occurred at seven of the eight nodes even under the 2-yr storm (3,671 m^3) and increased 7.6-fold to 27,732 m^3 for the 50-yr storm, with a cumulative flooding duration of 2.53–7.02 node-hours. These results match the common street flooding that happens in Alexandria during mild winter storms [2].

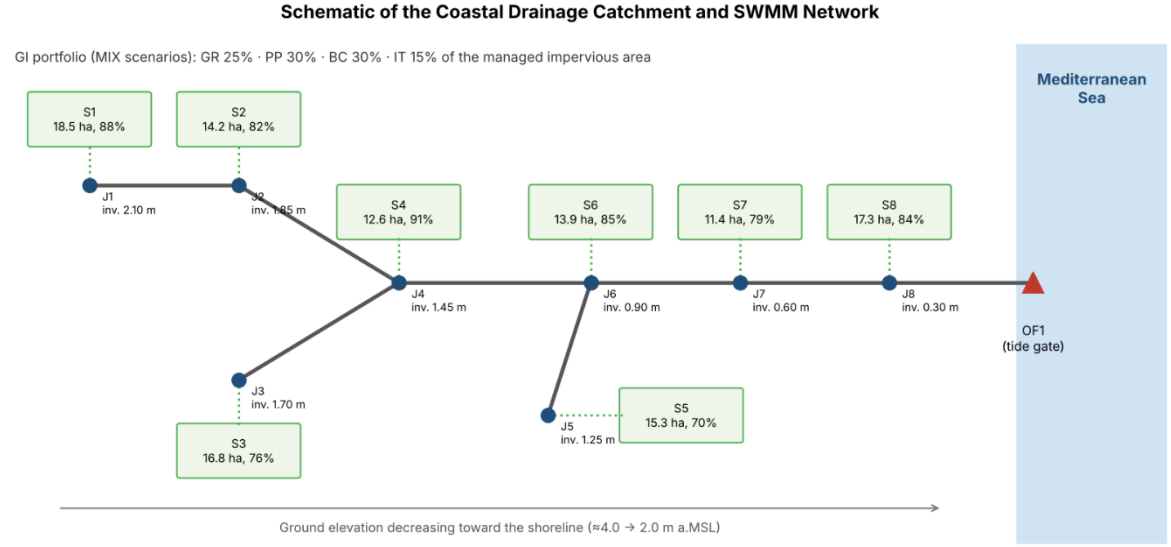


Figure 1. Schematic of the representative coastal catchment showing subcatchments S1–S8 (area, imperviousness), junction inverts, and the tide-gated outfall OF1.

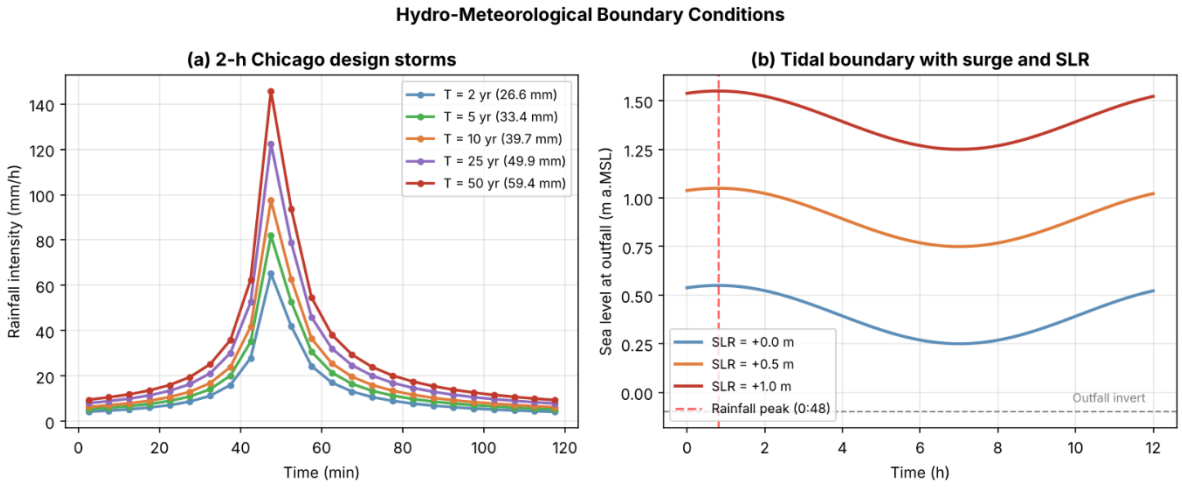


Figure 2. Boundary conditions: (a) 2-h Chicago design hyetographs for return periods of 2–50 yr and (b) sea level at the outfall for SLR scenarios of +0.0, +0.5 and +1.0 m.

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Table 2. Baseline Hydrological Response of the Coastal Catchment under Design Storms (SLR = +0.0 m).

Parameter	T = 2 yr	T = 5 yr	T = 10 yr	T = 25 yr	T = 50 yr
Rainfall depth (mm)	26.6	33.4	39.7	49.9	59.4
Peak 5-min intensity (mm/h)	65.2	82.0	97.5	122.5	145.7
Runoff depth (mm)	20.7	26.3	31.5	40.5	49.4
Runoff coefficient (–)	0.78	0.79	0.79	0.81	0.83
Infiltration (mm)	4.8	6.1	7.2	8.4	9.0
Peak runoff (m^3/s)	8.31	11.27	14.09	18.95	23.72
Peak outfall flow (m^3/s)	4.49	4.77	4.95	5.31	5.59
Flood volume (m^3)	3,671	7,611	11,693	19,466	27,732
Flooding duration (node-h)	2.53	3.70	4.52	5.80	7.02

Performance of Individual and Combined GI Practices

All the GI scenarios reduced the runoff and flooding levels from the 10-year storm (Figure 3). The highest water flow of 14.09 m^3/s during the baseline scenario was lowered to 10.77 m^3/s with MIX20 and further reduced to 9.14 m^3/s with MIX30.The peak flooding rate dropped from 9.10 m^3/s to 6.09 m^3/s and then to 4.56 m^3/s. The time it took for the flooding to happen also became shorter. The results of each individual practice are shown in Table 3. GR20 and PP20 had the same amount of runoff, 24.22 mm, which is a 23.1% decrease, because both kept all the rain that fell on the areas they were tested on. However, PP20 had less flooding, 5,040 cubic meters, which is a 56.9% reduction, compared to GR20's 6,179 cubic meters with a 47.2% reduction. This is because PP20 was better at storing water underground and letting it soak into the ground, with 20.0 mm of infiltration compared to 7.0 mm for GR20. BC20's small footprint and reliance on exfiltration resulted in a 30.7% reduction in flood volume, while IT20, meanwhile, had a significant reduction of 18.5%. The mixed portfolios showed a nearly straight increase in benefits as the extent increased: flood volume reductions were 20.3%, 40.2%, and 59.5% for MIX10, MIX20, and MIX30, respectively, and runoff coefficients went down from 0.79 to 0.73, 0.65, and 0.57.

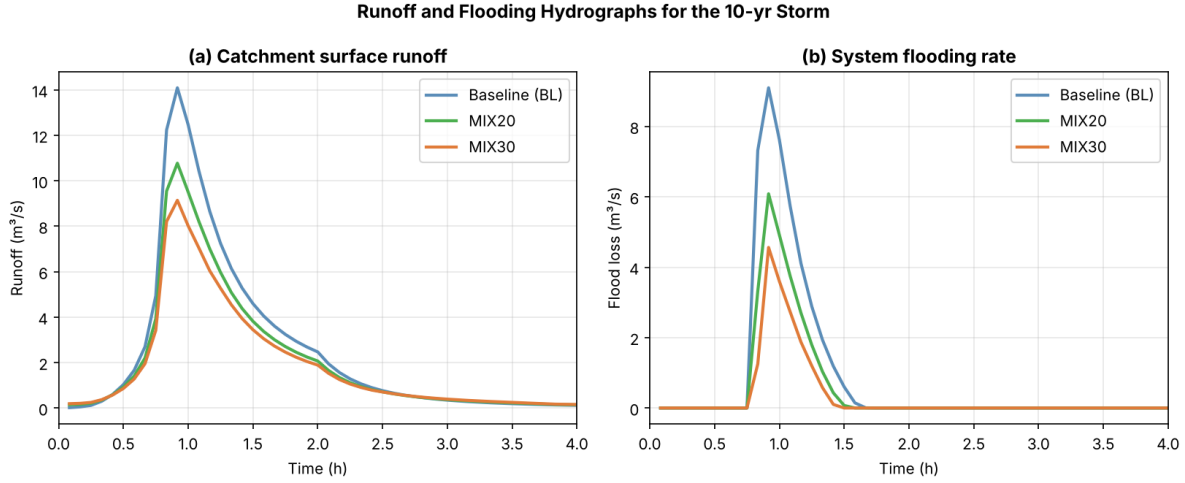


Figure 3. Hydrographs of (a) catchment surface runoff and (b) system flooding rate for BL, MIX20 and MIX30 under the 10-yr storm (SLR = +0.0 m).

Table 3. Hydrological Performance of GI Scenarios under the 10-yr, 2-h Design Storm (39.7 mm; SLR = +0.0 m).

Scenario	Runoff (mm)	Runoff coeff. (–)	Peak runoff (m^3/s)	Flood volume (m^3)	Flooding (node-h)	Flood reduction (%)
BL	31.51	0.79	14.09	11,693	4.52	—
GR20	24.22	0.61	10.30	6,179	3.47	47.2
PP20	24.22	0.61	10.11	5,040	2.76	56.9
BC20	26.86	0.68	11.16	8,103	3.95	30.7
IT20	29.22	0.74	11.20	9,529	4.38	18.5
MIX10	28.82	0.73	12.43	9,316	4.07	20.3
MIX20	25.89	0.65	10.77	6,987	3.58	40.2
MIX30	22.71	0.57	9.14	4,741	2.97	59.5

Effect of Storm Magnitude on GI Performance

The advantage of all GI situations became smaller as the time it took for an event to happen got longer, as shown in Figure 4. The amount of runoff that was reduced by MIX30 went down from 30.4% for a 2-year storm to 24.0% for a 50-year storm. The reduction in flood volume dropped even more, from 88.6% to 42.9%. The decrease was biggest for methods that rely on capturing water: the amount of flood volume lost by IT20 dropped from 55.5% to 7.8%, and for BC20 it went down from

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59.6% to 15.3%. This happened because their storage ran out before the biggest rainfall events reached their peak. In contrast, the source-replacement practices kept a bigger share of their benefits (GR20 decreased from 71.2% to 39.0%; PP20 decreased from 76.3% to 48.8%), and PP20 did better than MIX30 in reducing floods for return periods of 25 years and longer. The runoff reductions of GR20 and PP20 remained almost constant (22.3–23.1%) because the converted surfaces generated almost no runoff under any of the storms tested.

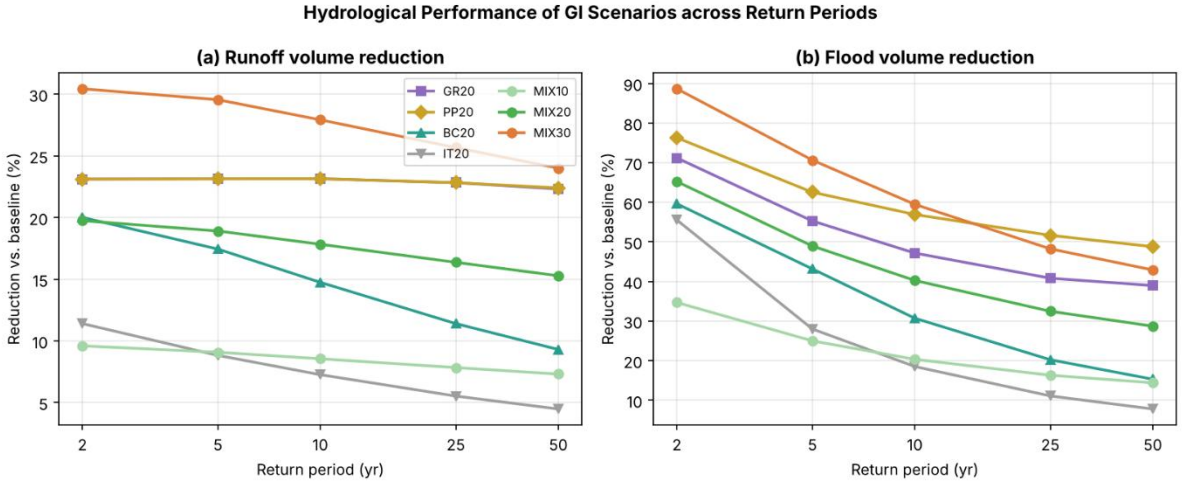


Figure 4. Reduction of (a) runoff volume and (b) flood volume relative to BL for all GI scenarios across return periods of 2–50 yr (SLR = +0.0 m).

Compound Flooding under Sea-Level Rise

Sea-level rise caused more flooding in every scenario shown in Figure 5. For the 10-year storm, a water level rise of +0.5 meters had a small impact, increasing BL flooding by just 1.9%, because the outfall gate stayed open during most of the event.However, a rise of +1.0 meters caused a bigger increase in BL flooding, raising it from 11,693 to 13,698 cubic meters and extending the total time the area was flooded from 4.52 to 5.12 node-hours. At a depth of 1.0 meter, the peak outfall discharge dropped from 4.95 to 4.32 cubic meters per second because the high tailwater level limited how much the gate could open, which shows that the network became tide-locked. The increase in flooding was bigger for the GI scenarios, with MIX20 showing a 23.6% rise and MIX30 a 30.5% rise. As a result, the benefit of reducing floods compared to the baseline (BL) dropped from 40.2% to 37.0% for MIX20 and from 59.5% to 54.8% for MIX30. Taking away the groundwater limit for MIX30 at +1.0 m lowered the flood volume from 6,185 to 5,981 m^3, which is a decrease of 204 m^3 or 3.4%. This shows that most of the impact from sea level rise came from the backwater at the outfall, not from less infiltration.

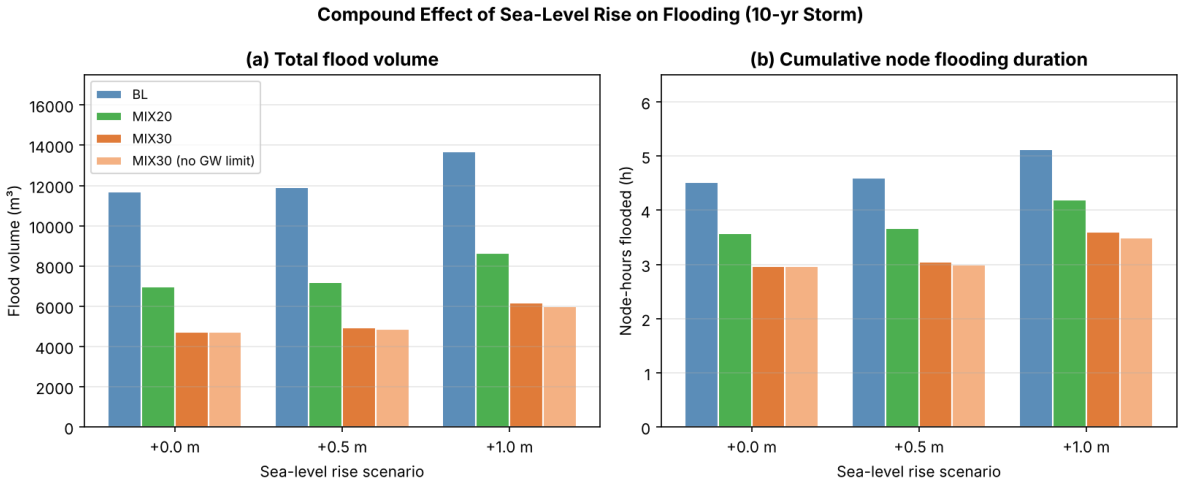


Figure 5. Effect of sea-level rise on (a) total flood volume and (b) cumulative flooding duration for BL, MIX20 and MIX30 with and without the groundwater (GW) constraint (10-yr storm).

Stormwater Quality Benefits

The drainage network received 5,097 kg of TSS (42.5 kg/ha), 98.2 kg of TN, and 14.35 kg/kg TP during the 10-year storm (BL). All the GI scenarios helped reduce these loads (Figure 6), with PP20 giving the biggest cuts among the single practices, reducing TSS by 48.3%, TN by 45.9%, and TP by 46.8%.GR20 came next, reducing TSS by 39.1%, TN by 33.0%, and TP by 29.0%. The decrease in pollution from BC20 (14.8–16.1%) and IT20 (8.6%) was smaller because only 20% of the non-porous area was directed to these practices, and some of the water flow went around them as overflow during the heaviest part of

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the storm. MIX10, MIX20, and MIX30 had lower TSS load reductions of 16.2%, 30.9%, and 44.4%, respectively, while the reductions for nutrients were slightly lower (TN 14.8–40.5%; TP 14.5–39.6%), which reflected the lower removal efficiencies for dissolved species.

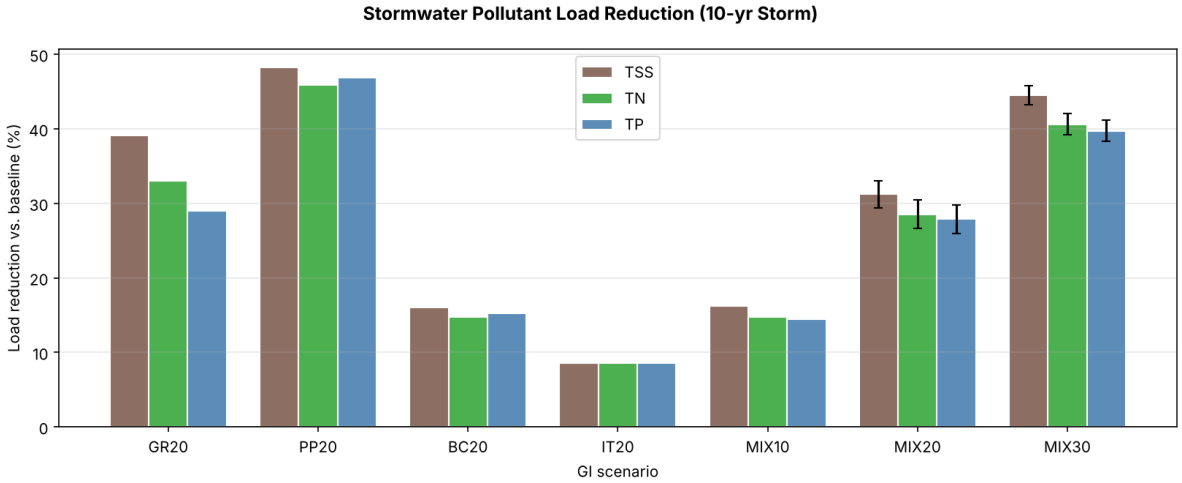


Figure 6. Reduction of TSS, TN, and TP event loads relative to BL for all GI scenarios under the 10-yr storm (error bars: ± SD of the Monte Carlo analysis, n = 60).

Table 4. Event Pollutant Loads Delivered to the Drainage Network under the 10-yr Storm and Reductions Relative to Baseline.

Scenario	TSS load (kg)	TN load (kg)	TP load (kg)	Reduction TSS / TN / TP (%)
BL	5,097	98.2	14.35	—
GR20	3,103	65.7	10.19	39.1 / 33.0 / 29.0
PP20	2,636	53.1	7.63	48.3 / 45.9 / 46.8
BC20	4,278	83.7	12.16	16.1 / 14.8 / 15.3
IT20	4,660	89.7	13.12	8.6 / 8.6 / 8.6
MIX10	4,272	83.7	12.27	16.2 / 14.8 / 14.5
MIX20	3,521	70.5	10.39	30.9 / 28.2 / 27.6
MIX30	2,835	58.4	8.67	44.4 / 40.5 / 39.6

Uncertainty and Statistical Significance

The Monte Carlo flood volumes for the 10-year storm are as follows: BL is 11.86 ± 1.04 × 10^3 m^3, MIX20 is 7.10 ± 0.78 × 10^3 m^3, and MIX30 is 4.70 ± 0.62 × 10^3 m^3. These represent average reductions of 40.1% and 60.4%, which are very close to the deterministic values, within 0.9 percentage points. The depth of runoff (BL 31.72 ± 0.86 mm; MIX30 22.81 ± 0.60 mm) and the highest amount of runoff (BL 14.14 ± 0.66 m^3/s; MIX30 9.21 ± 0.33 m^3/s) had variation values less than 5%. However, the total volume of flood water was more affected by the parameters, with variation percentages of 8.8% for BL and 13.2% for MIX30. The one-way ANOVA showed very large differences between the scenarios for all the response variables ($F = 1,146–2,252$; $p < 0.001$). Then, Tukey's HSD test showed that all the comparisons between pairs (BL vs. MIX20, BL vs.MIX30, and MIX20 vs.MIX30) were also significant ($p < 0.001$). All the data from this analysis is listed in Table 5.

Table 5. Monte Carlo Results for BL, MIX20 and MIX30 under the 10-yr Storm (n = 60, mean ± SD).

Variable	BL	MIX20	MIX30	ANOVA F (p)
Runoff depth (mm)	31.72 ± 0.86	25.95 ± 0.75	22.81 ± 0.60	2,200.6 (< 0.001)
Peak runoff (m^3/s)	14.14 ± 0.66	10.73 ± 0.40	9.21 ± 0.33	1,641.1 (< 0.001)
Flood volume (10^3 m^3)	11.86 ± 1.04	7.10 ± 0.78	4.70 ± 0.62	1,146.4 (< 0.001)
Flooding (node-h)	4.59 ± 0.59	3.66 ± 0.50	2.92 ± 0.44	—
TSS load (kg)	5,132 ± 140	3,530 ± 93	2,847 ± 64	2,251.6 (< 0.001)
TN load (kg)	98.8 ± 2.7	70.7 ± 1.9	58.7 ± 1.4	1,525.9 (< 0.001)
TP load (kg)	14.44 ± 0.40	10.41 ± 0.28	8.71 ± 0.20	1,384.6 (< 0.001)

Discussion

The reductions in runoff volume from the mixed portfolios (8.6–27.9% for the 10-year storm) and the bigger decreases in peak runoff (11.8–35.1%) and flood volume (20.3–59.5%) match the ranges found in large-scale reviews of LID performance [7, 8, 15]. The big impact of flooding compared to the amount of water running off is because of limited capacity in the system: since flooding happens when water flows faster than the system can handle, cutting back a little on the incoming

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water can greatly reduce the amount of flooding. This non-linearity shows that even small changes in the GI system can lead to big improvements in flood risk reduction, especially in networks that aren't properly designed, like those in Alexandria [2]. The steady relationship between flood reduction and the area being managed (about 2% less flooding for every 1% of impervious area controlled) offers a straightforward way to plan during the early design phase.

The superior performance of permeable pavement and green roofs in this study is due to their replacement of impervious surfaces, which eliminates runoff generation at the source, whereas bioretention cells and infiltration trenches must capture runoff from a contributing area that is much larger than their footprint. The big storage and ability to move water of the PP sub-base give it an edge over GR, which matches what Drake et al. [11] found in their review of permeable pavement performance. However, green roofs can't hold much water because they usually have thin soil layers, as noted in [12]. The high loading ratio of the trenches (25:1) is the reason for IT20's poor performance, rather than an inherent limitation; the use of larger footprints or a combination with underdrains would enhance its efficiency. The fixed portfolio used here is a safe mix, and a portfolio that includes more PP and GR would work better in areas with lots of parking and rooftops.

The less benefit from GI becomes as the time between storms gets longer, which matches the findings of Qin et al.[9]. They found that LID works best for smaller and more frequent rain events, but its impact on flooding becomes smaller during heavy rainfall. In the current study, the capture-based practices were no longer storing water before the peak of the 25- and 50-yr storms, leading to a nearly unattended transmission of peak inflow to the network. This behaviour has two practical implications. The main goal of GI should be to stop frequent minor flooding and handle the first part of runoff, which is when it works best. Second, events like the 2015 Alexandria flood [2] need extra solutions such as more water flow, pumping, holding areas, and ways to handle extra water. This means green infrastructure works as part of a combined system that includes both green and traditional methods [1], not as a replacement for them.

The results show that the coastal edge changes how well GI works in two different ways. Higher sea levels make it harder for wastewater to flow out (called tide-locking), so rainwater gets stuck in the pipes and flows over the top at the lowest points. This process is the main reason for increased flooding, contributing more than 85% of the extra flooding seen in MIX30 at a sea level rise of 1.0 meter. Additionally, the elevation of the water table reduces the infiltration capacity of soils and LID storage layers, which is in line with the groundwater inundation processes observed in coastal cities [6, 7]. Because these effects happen at the lower part of the system, they make the GI less effective exactly where flooding is worst. The bigger increase in flooding under the GI scenarios, like +30.5% for MIX30 compared to +17.1% for BL, shows that using green infrastructure alone can't counteract the combined impacts of more rain and rising sea levels, as explained by Wahl et al.[4] and Moftakhari et al. [5]. In low-lying deltaic cities, GI should be used together with tide-gate management, pumped outfalls, and methods like lining or detention systems in places where groundwater is close to the surface.

The decreases in pollutant levels (up to 44.4% for TSS and about 40% for TN and TP under MIX30) show that green infrastructure helps improve water quality in ways that traditional drainage systems cannot. This is especially important for keeping coastal swimming areas and water bodies like Lake Maryut clean and safe. The smaller decreases in nutrients are because bioretention systems and permeable pavement don't remove much dissolved nitrogen, as found by Davis et al. [10] and Drake et al. [11], and there's a chance phosphorus could leak from the materials used in green roofs [12]. The Monte Carlo analysis found that the order of the scenarios didn't change much even when the main parameters varied by plus or minus 20%, but the flood volume was less certain than the runoff variables. Because the model wasn't checked against real-world water flow data, the numbers should just be considered as general ideas; to use the results for specific designs, the model needs to be adjusted with data from Alexandria and should also show how water flows over land in two dimensions.

Conclusion

This research finds that GI systems can greatly decrease stormwater runoff, flooding, and the amount of pollution in a low-lying coastal urban area similar to Alexandria, Egypt. A detailed study using SWMM modeling included eight different situations, five levels of storm frequency, three possible future sea level rise scenarios, and 180 random simulations. The results showed that as the percentage of managed impervious areas increased from 10% to 30%, the ability to reduce stormwater runoff volume, peak runoff, flood volume, and pollution levels also improved. For a 10-year storm event, the reductions were 27.9% in runoff volume, 35.1% in peak runoff, 59.5% in flood volume, and between 39.6% and 44.4% in pollution levels. Permeable pavement was the most effective single method used. However, the benefits of all the practices got smaller as storms became bigger and as sea levels rose. For example, the flood reduction from MIX30 dropped from 88.6% for a 2-year storm to 42.9% for a 50-year storm. Also, under a 1-meter rise in sea level, the flood reduction decreased from 59.5% to 54.8%. This happened mainly because the outfall got stuck with the tide. Based on these results, GI should be used as the main approach in coastal cities to handle frequent storms and control water quality, and it should work together with grey infrastructure and outfall management during extreme combined events. Future studies will look into: first, checking and making sure the model works well by comparing it with real data on rainfall, water flow, and sea levels; second, using a combination of 1D and 2D models to better understand flooding on land; third, finding the best way to spread out green infrastructure solutions in a way that is both effective and cost-efficient; and fourth, running long-term simulations to see how things might change under future rainfall patterns caused by climate change along the Egyptian Mediterranean coast.

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Conflicts of Interest
The authors declare no conflicts of interest.

Data Availability Statement
The SWMM input files, simulation scripts, and model outputs supporting the conclusions of this study are available from the corresponding author upon reasonable request.

References

1. Fletcher TD, et al. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water J. 2015;12(7):525-42. doi:10.1080/1573062X.2014.916314.
2. Zevenbergen C, Bhattacharya B, Wahaab RA, Elbarki WAI, Busker T, Salinas Rodriguez CNA. In the aftermath of the October 2015 Alexandria Flood: Challenges of an Arab city to deal with extreme rainfall storms. Nat Hazards. 2017;86(2):901-17. doi:10.1007/s11069-016-2724-z.
3. Hereher ME. Vulnerability of the Nile Delta to sea level rise: an assessment using remote sensing. Geomatics Nat Hazards Risk. 2010;1(4):315-21. doi:10.1080/19475705.2010.516912.
4. Wahl T, Jain S, Bender J, Meyers SD, Luther ME. Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nat Clim Change. 2015;5(12):1093-7. doi:10.1038/nclimate2736.
5. Moftakhari HR, Salvadori G, AghaKouchak A, Sanders BF, Matthew RA. Compounding effects of sea level rise and fluvial flooding. Proc Natl Acad Sci U S A. 2017;114(37):9785-90. doi:10.1073/pnas.1620325114.
6. Habel S, Fletcher CH, Rotzoll K, El-Kadi AI. Development of a model to simulate groundwater inundation induced by sea-level rise and high tides in Honolulu, Hawaii. Water Res. 2017;114:122-34. doi:10.1016/j.watres.2017.02.035.
7. Ahiablame LM, Engel BA, Chaubey I. Effectiveness of low impact development practices: Literature review and suggestions for future research. Water Air Soil Pollut. 2012;223(7):4253-73. doi:10.1007/s11270-012-1189-2.
8. Eckart K, McPhee Z, Bolisetti T. Performance and implementation of low impact development – A review. Sci Total Environ. 2017;607-608:413-32. doi:10.1016/j.scitotenv.2017.06.254.
9. Qin HP, Li ZX, Fu G. The effects of low impact development on urban flooding under different rainfall characteristics. J Environ Manage. 2013;129:577-85. doi:10.1016/j.jenvman.2013.08.026.
10. Davis AP, Hunt WF, Traver RG, Clar M. Bioretention technology: Overview of current practice and future needs. J Environ Eng. 2009;135(3):109-17. doi:10.1061/(ASCE)0733-9372(2009)135:3(109).
11. Drake JAP, Bradford A, Marsalek J. Review of environmental performance of permeable pavement systems: State of the knowledge. Water Qual Res J Can. 2013;48(3):203-22. doi:10.2166/wqrjc.2013.055.
12. Berndtsson JC. Green roof performance towards management of runoff water quantity and quality: A review. Ecol Eng. 2010;36(4):351-60. doi:10.1016/j.ecoleng.2009.12.014.
13. Rossman LA. Storm Water Management Model User's Manual, Version 5.1. Cincinnati (OH): U.S. Environmental Protection Agency; 2015. Report No.: EPA/600/R-14/413b.
14. Rossman LA, Huber WC. Storm Water Management Model Reference Manual. Volume III: Water Quality. Cincinnati (OH): U.S. Environmental Protection Agency; 2016. Report No.: EPA/600/R-16/093.
15. Dietz ME. Low impact development practices: A review of current research and recommendations for future directions. Water Air Soil Pollut. 2007;186(1-4):351-63. doi:10.1007/s11270-007-9484-z.

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